REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggesstions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any oenalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
11-09-2011	Final Report	15-Sep-2008 - 14-Sep-2011

4. TITLE AND SUBTITLE
Final Report for Project W911NF0810449 titled Energy Efficient Signal Detection for Army Applications Based on Ordering

5a. CONTRACT NUMBER
W911NF-08-1-0449

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Rick S. Blum

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Lehigh University
Office of Research & Sponsored Programs
Lehigh University
Bethlehem, PA   18015 -

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
54261-NS.59

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Several DoD agencies, including the U. S. Army have been committed to employing networks of sensors, often on unmanned platforms, to achieve battlefield superiority. However, as a recent report by the Committee on Network Science for Future Army Applications (a part of the National Research Council of the National Academies) indicates, network science is in its infancy. The report warns the theory of network operation is lacking and that study is needed to remedy this deficiency. Here we attempt to take some steps towards better fundamental

15. SUBJECT TERMS
Ordering, Energy Efficient Signal Processing, Order Statistics, Sequential Detection, Signal detection, Estimation, Classification

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Rick Blum
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					610-758-3459

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report for Project W911NF0810449 titled Energy Efficient Signal Detection for Army Applications Based on Ordering

ABSTRACT

Several DoD agencies, including the U. S. Army have been committed to employing networks of sensors, often on unmanned platforms, to achieve battlefield superiority. However, as a recent report by the Committee on Network Science for Future Army Applications (a part of the National Research Council of the National Academies) indicates, network science is in its infancy. The report warns the theory of network operation is lacking and that study is needed to remedy this deficiency. Here we attempt to take some steps towards better fundamental understanding of sensor networks, a very important topic for the U. S. Army, with a particular focus on signal detection and estimation applications. The overall objective of this effort is to develop new network communication and signal processing (sensor processing) protocols for signal detection and estimation applications which will be energy efficient and robust. We have developed one approach called ordering which saves energy without any loss of performance. The approach was developed first for signal detection applications and more recently for estimation applications. The approach has been shown to be useful for networks of radar sensors, often called MIMO radars, which have also been investigated in this project.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper

TOTAL: **18**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>   <u>Paper</u>

  TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

  TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

2011/09/06 2(58   . Noncoherent Versus Coherent MIMO Radar for Joint TargetPosition and Velocity Estimation, 2011 IEEE CIE International Conference on Radar. 2011/10/24 00:00:00, . : ,

2011/09/06 2(57   Rick S. Blum, Qian He. Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction Hypothesis Test, ICSGCE 2011. 2011/09/27 00:00:00, . : ,

2011/09/03 2: 56   Qian He, Rick S. Blum. New hypothesis testing-based methods for fault detection for smart grid systems, 2011 45th Annual Conference on Information Sciences and Systems (CISS). 2011/03/23 00:00:00, Baltimore, MD, USA. : ,

2011/09/03 2: 55   Ziad N. Rawas, Qian He, Rick S. Blum. Energy-efficient noncoherent signal detection for networked sensors using ordered transmissions, 2011 45th Annual Conference on Information Sciences and Systems (CISS). 2011/03/23 00:00:00, Baltimore, MD, USA. : ,

2011/09/03 2: 54   Qian He, Rick S. Blum. MIMO radar diversity with Neyman-Pearson signal detection in non-Gaussian circumstance with non-orthogonal waveforms, ICASSP 2011 - 2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). 2011/05/22 00:00:00, Prague, Czech Republic. : ,

2011/09/03 2: 53   Qian He, Rick S. Blum. Smart grid monitoring for intrusion and fault detection with new locally optimum testing procedures, ICASSP 2011 - 2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). 2011/05/22 00:00:00, Prague, Czech Republic. : ,

2011/09/03 2: 52   Rick S. Blum. Ordering for energy efficient estimation and optimization in sensor networks, ICASSP 2011 - 2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). 2011/05/22 00:00:00, Prague, Czech Republic. : ,

2011/09/03 2: 51   Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum. Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Metrics, International Conference on Information Fusion. 2011/06/06 00:00:00, . : ,

2011/09/03 2: 50   Qian He, Rick S. Blum. Diversity gain for MIMO radar employing nonorthogonal waveforms, 2010 4th International Symposium on Communications, Control and Signal Processing (ISCCSP). 2010/03/03 00:00:00, Limassol, Cyprus. : ,

2011/09/03 2: 49   Yang Yang, Rick S. Blum, Brian M. Sadler. Distributed energy-efficient scheduling for radar signal detection in sensor networks, 2010 IEEE Radar Conference. 2010/05/10 00:00:00, Arlington, VA, USA. : ,

2011/09/03 2: 48   Rick S. Blum. Ordering for estimation, 2010 44th Annual Conference on Information Sciences and Systems (CISS). 2010/03/17 00:00:00, Princeton, NJ, USA. : ,

2011/09/03 2: 47   Xun Chen, Rick Blum. Non-coherent MIMO radar in a non-Gaussian noise-plus-clutter environment, 2010 44th Annual Conference on Information Sciences and Systems (CISS). 2010/03/17 00:00:00, Princeton, NJ, USA. : ,

2011/09/03 2: 46   Chuanming Wei, Qian He, Rick S. Blum. Cramer-Rao bound for joint location and velocity estimation in multi-target non-coherent MIMO radars, 2010 44th Annual Conference on Information Sciences and Systems (CISS). 2010/03/17 00:00:00, Princeton, NJ, USA. : ,

2011/09/03 2: 45   Yang Yang, Rick S. Blum, Zishu He, Daniel R. Fuhrmann. Alternating projection for MIMO radar waveform design, 2009 3rd IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP). 2009/12/13 00:00:00, Aruba. : ,

2011/09/03 2: 44   Yang Yang, Rick S. Blum, Zishu He, Daniel R. Fuhrmann. Waveform design for MIMO radar using an alternating projection approach, 2009 Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers. 2009/11/01 00:00:00, Pacific Grove, CA, USA. : ,

2011/09/03 2: 43   Vlad M. Chiriac, Alexander M. Haimovich, Rick S. Blum, Hana Godrich. Target tracking in MIMO radar systems: Techniques and performance analysis, 2010 IEEE Radar Conference. 2010/05/10 00:00:00, Arlington, VA, USA. : ,

2011/09/03 2: 42   Hana Godrich, Alexander M. Haimovich, Rick S. Blum. A MIMO radar system approach to target tracking, 2009 Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers. 2009/11/01 00:00:00, Pacific Grove, CA, USA. : ,

2011/09/03 2: 41   Rick S. Blum, Qian He. Performance and complexity issues in noncoherent and coherent MIMO radar, 2009 Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers. 2009/11/01 00:00:00, Pacific Grove, CA, USA. : ,

TOTAL: 18

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2011/05/23 2.	26	R. S. Blum. Ordering for Estimation, conference on information sciences and systems (01 2010)
2011/05/23 2.	25	Rick S. Blum. Ordering for Estimation and Optimization in Energy Efficient Sensor Networks, IEEE Transactions on Signal Processing (01 2011)
2011/05/23 2.	24	Qian He and R. S. Blum. Diversity Gain for MIMO Neyman-Pearson Signal Detection, IEEE Transactions on Signal Processing (01 2011)
2010/07/27 1(	23	Qian He, Rick S. Blum, . Diversity Gain for MIMO Neyman-Pearson Signal Detection, IEEE Transactions on Signal Processing (04 2010)
2010/07/26 2(	22	Rick S. Blum. Ordering for Estimation and Optimization in Energy Efficient Sensor Networks, IEEE Transactions on Signal Processing (07 2010)
2010/07/26 2(	21	Chuanming Wei, Lance M. Kaplan, Stephen D. Burks, Rick S. Blum. Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Measures, IEEE Transactions on Image Processing (07 2010)
2010/01/24 1.	19	Zhemin Xu, Sana Sfar, Rick S. Blum. submitted manuscript: Receive Antenna Selection for Closely-Spaced Antennas with Mutual Coupling, IEEE Transactions on Wireless Communications (01 2010)
2010/01/24 1.	18	Zhemin Xu, Rick S. Blum, Brian M. Sadler. submitted manuscript: Sensor Selection Based on Sensor Observations for Energy Efficient Hypothesis Testing, IEEE Transactions on Signal Processing (11 2009)
2010/01/23 2:	17	Q. He, R. S. Blum, and A. M. Haimovich. Noncoherent versus coherent MIMO radar: Simplicity with little loss for sufficient numbers of antennas, IEEE Transactions on Signal Processing (12 2009)
2010/01/23 1(	15	Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum. Submitted Manuscript: Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Measures, IEEE Transactions on Image Processing (12 2009)
2010/01/23 1.	13	Q. He and R. S. Blum. Manuscript appearing: Q. He and R. S. Blum. "Cramer-Rao bound for MIMO radar target localization with phase errors," IEEE Signal Processing Letters, vol. 17, no. 1, pp. 83-86, Jan 2010. , IEEE Signal Processing Letters (01 2010)
2009/09/03 0!	12	Y.Yang, R.Blum, Z.He, D.Fuhrmann. Alternating Projection for MIMO Radar Waveform Design, ( )
2009/09/03 0!	11	Y. Yang, R. Blum. Distributed Energy-Efficient Scheduling for Fluctuating Signal Detection in Sensor Networks, ( )
2009/09/03 0!	10	Y. Yang, R. Blum, Z. He, D. Fuhrmann. MIMO Radar Waveform Design via Alternating Projection, ( )
2009/09/03 0!	9	Y.Yang, R.Blum, S. Sfar. Antenna Selection for MIMO Systems with Closely Spaced Antennas, ( )
2009/09/03 0!	8	Y. Yang, R. Blum, B. Sadler. A Distributed and Energy-Efficient Cross-Layer Framework for Neyman-Pearson Detection of Fluctuating Signals in Large-Scale Sensor Networks, ( )
2009/09/03 0{	7	Q. He, R. Blum, A. Haimovich. Cramer-Rao Bound for MIMO Radar Target Localization with Phase Errors, ( )
2009/09/03 0{	6	Q. He, R. Blum, A. Haimovich. Non-coherent MIMO Radar for Location and Velocity Estimation: More Antennas Means Better Performance, ( )
2009/09/03 0{	5	Q. He, R. Blum, H. Godrich, A. Haimovich. Target Velocity Estimation and Antenna Placement for MIMO Radar with Widely Separated Antennas, ( )
2009/09/03 0{	4	H. Godrich, A. Haimovich, R. Blum. Target Localization Accuracy Gain in MIMO Radar Based Systems, ( )
2009/09/03 0{	3	Q. He, N. Kehmann, R. Blum, A. Haimovich. MIMO Radar Moving Target Detection in Homogeneous Clutter, ( )

TOTAL: 21

Number of Manuscripts:

Books

<u>Received</u>   <u>Paper</u>

TOTAL:

Patents Submitted

Patents Awarded

Awards

The PI was named an IEEE Signal Processing Society distinguished lecturer.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Anand Srinivas	0.20	
Joe Baker	0.20	
Liang Zhao	0.20	
Chuanming Wei	0.40	
FTE Equivalent:	**1.00**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Yang Yang	0.20
Qian He	0.20
FTE Equivalent:	**0.40**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Rick S. Blum	0.40	
FTE Equivalent:	**0.40**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Ziad Rawas
Joe Baker

Total Number: **2**

Names of personnel receiving PHDs

NAME
Xun Chen
Zhemin Xu
Qian He
Yang Yang

Total Number: **4**

Names of other research staff

NAME   PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Scientific Progress

Energy Efficient Signal Detection for Army
Applications Based on Ordering, ARO Grant No.
W911NF-08-1-0449 (Submitted Sept. 2011)

Principal Investigator: Rick S. Blum
Electrical Engineering and Computer Science Dept.
Lehigh University
19 Memorial Drive West
Bethlehem, PA 18015-3084

1. Objectives

Networks of sensor nodes offer enhanced performance
along with some inherent limitations, among which the most
prominent one is probably that each sensor node is constrained
in energy supply since these nodes often carry their own energy
sources. UAVs are one example. Limited available communication
resources are also common. Under this grant, we demonstrated
that these challenges can be addressed by jointly designing the
signal processing and communications.   We developed an approach
called "ordering" where each sensor is able to judge the importance
of its data, without seeing the data at the other sensors. The
importance is judged based on the signal processing problems
the system is trying to solve, for example estimation and detection.
The sensors with the most informative data transmit their data first
and the sensors with less important data can save energy by not
transmitting. With a proper transmission stopping rule, this
approach yields the same performance as if all sensors transmit
and yet very impressive energy savings are achieved in many cases
of interest (significant SNR or number of sensors or proper system
design). We initially demonstrated the gains at the physical layer
of the communication network for networks attempting to solve signal
detection problems. Later we demonstrated appropriate higher layer
designs to capitalize on these gains while also showing the ordering
approach is appropriate for networks attempting to solve estimation,
optimization, or classification problems. We demonstrated the power
of the ordering approach on MIMO radar network examples, networks
of widely spaced antennas or radar nodes. We also made some fundamental
contributions to the theory of MIMO radar, in some cases capitalizing
on our knowledge of both communications and signal processing, and in
particular radar. The high citation rates and great interest from the
radar community (including now DoD contractors) indicate the
importance of this work.

2. Executive Summary

We have made excellent progress on studying joint design of signal processing
and communication strategies for networks of dispersed nodes where each
node may be equipped with a sensor. One area of focus has been on developing
appropriate signal processing and communication strategies for networks
which focus on target detection or hypothesis testing problems. There
are many important military and non-military applications of this paradigm,
including MIMO radar which is attracting great attention in the research,
development and funding communities. MIMO radar is one focus of this
work. However, the investigations here are also much more general.
In particular, hypothesis testing, often called signal detection, is a
fundamental sensor networking application which is key for solving
many important problems including improved monitoring, control and
repair of the human body, buildings, bridges, energy production

facilities, the environment and other critical infrastructure, while also providing important contributions to homeland security, law enforcement, disaster prediction/avoidance and defense related problems. For example, we had some collaboration with faculty in the civil engineering department at Lehigh University on monitoring the health of large structures (for example bridges, buildings and airplanes) to detect problems before they occur. In fact there are many applications of this type which directly fit our paradigm. There are also some applications that indirectly fit our paradigm. For example, we also had collaboration with scientists in the Biological Sciences department at Lehigh University, who are working on understanding biological systems. In their scientific experiments they typically pose hypothesis testing problems and attempt to test the hypothesis using sensor measurements. Interestingly, in these applications it is important to limit the number of measurements to avoid damaging the living organisms under study. In this case we limit sensor measurements for a different reason, as opposed to trying to save precious battery power, but our general theory still applies. Of course, our main focus has been on military applications. We have developed very promising approaches for saving battery power and transmission rates for important military applications employing sensors. For example, we developed a highly efficient approach, called ordering, which saves significant energy or transmission rate for target detection and estimation.

Out of necessity, a second area of investigation has been on developing MIMO radar signal processing technology and also similar ideas for more general sensor networks. In presenting and discussing some of our research on ordering applied to MIMO radar systems, some fundamental ideas about MIMO radar became clear to us. As the group that is most often credited with initiating the current high level of interest in MIMO radar by developing and describing the MIMO radar concept, we are still a bit ahead of others and we were lucky to be well positioned to act quickly on some important research opportunities that became evident. More recently we are getting lots of interest from DoD contractors who want to employ MIMO radar ideas into future DoD radar systems which is very exciting. These discussions have lead to a few research discoveries which were completed under this funding.

3. Accomplishments (all references from list in Section 5)

Our very recent work on applying ordering to estimation and optimization problems [14,22,26] is especially exciting. A discretized version of a continuous optimization problem is considered for the case where data is obtained from a set of dispersed sensor nodes and the overall metric is a sum of individual metrics computed at each sensor. An example of such a problem is maximum likelihood estimation based on statistically independent sensor observations [4,5,9,16,20,32]. By ordering transmissions from the sensor nodes, a method for achieving a saving in the average number of sensor transmissions is described. While the average number of sensor transmissions is reduced, the approach always yields the same solution as the optimum approach where all sensor transmissions occur. The approach is valid for a general optimization or estimation problem. A maximum likelihood target location and velocity estimation example for a multiple node non-coherent MIMO radar system was investigated in great detail [14,22,26]. In particular, for cases with N good quality sensors with sufficiently well designed signals and sufficiently large signal-to-interference-plus-noise ratio, the average percentage of transmissions saved approaches 100 percent as the number of discrete grid points in the optimization problem Q becomes significantly large. In these same cases, the

average percentage of transmissions saved approaches (Q-1)/Q x 100 percent as the number of sensors N in the network becomes significantly large. Similar savings are illustrated for general optimization (or estimation) problems with sufficiently well designed systems. Savings can be even larger in some cases for systems with some poor quality sensors. One important result is that timing errors, clock errors and unknown communication delays can be overcome without significant impact in many applications [14].

We have also made some contributions to the topic of applying ordering to signal detection problems under this grant.   The robustness due to timing errors, clock errors and unknown communication delays described in [14] also applies here since [14] describes a general method to put "out of order" transmissions back in order. We have also shown that the ordering for detection ideas we published earlier do apply to MIMO radar systems [29]. Further, the gains for the MIMO radar application are even larger than the gains reported earlier. First, we have provided [29] an improved ordering approach for any noncoherent processing approach and the MIMO radar system considered in [29] is one such approach. Second, we show [29] that the gains are very large for practical systems with very small false alarm probabilities. Finally, we have discussed [8,23] a methodology for implementing ordering approaches in radar systems by describing an efficient implementation of some of the important subsystems required.

We have also made progress in our studies of networks of radar sensors, showing [9,16,20,32] that we can control the performance of both the non-coherent and coherent approaches by the number of antennas employed. In particular the improvements in estimation position and velocity estimation scale directly in proportion to the product of the number of transmitter antennas times the number of receiver antennas as shown in [9], and to a lesser extent [1,4,5,11,15,16,17,20,32]. Similar gains occur for detection problems [2,10,13,21,28,29]. These estimation results [9,16] are very important in justifying the value of the noncoherent approach by showing [32] that the non-coherent approach can be made to perform sufficiently close to a coherent approach if a sufficient number of properly placed antennas are employed. Our fundamental investigations on the accuracy of the approaches for target estimation in ideal [1,5,9,11] and nonideal [4] settings have also demonstrated significant potential for MIMO radar. In fact, slow oscillator phase drifts or static phase errors may not be such a big problem [4] for MIMO radar.

MIMO radar has brought attention to diversity gains that occur in radar systems that are similar to the diversity gains that occur in communication systems. We have recently demonstrated that one needs complex targets to get these gains [2] but that orthogonal signals, Gaussian reflections and Gaussian clutter are not needed [13]. In particular, our results in [13] show that the diversity gain of the non-coherent MIMO radar approach is not dependent on the clutter-plus-noise distribution for any well behaved (finite power) clutter model. We are particularly excited about our findings on diversity in non-Gaussian clutter-plus-noise [13]. For a radar system adopting the Neyman-Pearson (NP) criterion, we have derived the diversity gain for a general scalar hypothesis test statistic and a general vector hypothesis testing problem.

For a MIMO radar system with M transmit and N receive antennas, used to detect a target composed of Q random scatterers with possibly non-Gaussian reflection coefficients in the presence of possibly non-Gaussian clutter-plus-noise, in [13] we considered a class of

test statistics, including the optimum test for Gaussian reflection coefficients and Gaussian clutter-plus-noise, and applied the previously described general (last paragraph) results to compute the diversity gain. It was found that the diversity gain for the MIMO radar system is dependent on the cumulative distribution function (cdf) of the reflected signal (and thus it depends on the distribution of the reflection coefficients) while being invariant to the cdf of the bounded variance clutter-plus-noise. If the transmitted waveforms span a dimension L, the largest possible diversity gain is no greater than p min(NL,Q), where p is the lowest order coefficient of a Taylor series expansion of the cdf of the reflected signal and L can be no greater than M. Thus orthogonal signals are not need to achieve the largest possible diversity gain of p min(NM,Q), only linear independence. In some cases of interest (independent reflections), it is shown that the maximum possible diversity gain can be achieved.

We were also able to demonstrate [10] a new gain, called geometry gain, in MIMO radar moving target detection applications that looks a bit like a diversity gain but which is distinctly different. It comes from viewing the motion of the target from different directions and developing the estimated (fused) motion to be consistent with all these views. We have received some significant interest from industry in these results due to the practical importance and difficult nature of this problem. Similarly, industry and academia are both very interested in waveform design for MIMO radar. We have studied this problem for classification and high resolution estimation applications in [6,18,19]. Here we were able to extend some of our previous theoretical results that showed an equivalence between optimizing for mean-square error and mutual information. The previous results demonstrated the equivalence without producing the actual waveforms. In [6,18,19], we provided an algorithm to produce actual waveforms and we showed these practical waveforms produced results that were indistinguishable from our previous theoretical predictions in a large number of example cases considered. Thus, these practical waveforms jointly optimized mean-square error and mutual information for the example cases considered to the highest accuracy we could achieve in our computations. We were recently the first group to demonstrate large potential gains in tracking performance from employing a MIMO radar and in [17,33] we study the effect of the antenna positions, target location, path loss, target reflectivity, and the number of antennas (radar nodes) employed.

Some other contributions to image fusion, communications and smart grid are reported in [3,7,12,,25,27,30,31]. Here we have tried to use some of the ideas and techniques studied under this funding for some different applications from those previously considered, mainly radar and sensor networking.

4. Personnel Supported

Rick S. Blum, (PI) Professor of ECE
Xun Chen, Research Assistant
Jim Davis, Research Assistant
Ziad Rawas, Research Assistant
Zhemin Xu, Research Assistant
Qian He, Research Assistant
Yang Yang, Research Assistant
Anand Srinivas Guruswamy, Research Assistant
Joe Baker, Research Assistant
Chuanming Wei, Research Assistant
Liang Zhao, Research Assistant
Qian He, postdoc
Yang Yang, Postdoc

5. Technical Publications

Journal Papers
----

1. Hana Godrich, Alexander Haimovich, Rick S. Blum, ``Target Localisation Techniques and Tools for multiple-input multiple-output radar,'' Radar, Sonar & Navigation, IET, Vol. 3, Issue 4, pp. 314-327, Aug. 2009.

2. Rick S. Blum, "Limiting Case of a Lack of Rich Scattering Environment for MIMO Radar Diversity", IEEE Signal Processing Letters, Volume 16, Issue 10, Oct. 2009, pp. 901-904.

3. Chuanming Wei and Rick S. Blum, ``Theoretical analysis of correlation-based quality measures for weighted averaging image fusion,''Information Fusion (10 November 2009).

4. Qian He, Rick S. Blum, "Cramer-Rao Bound for MIMO Radar Target Location with Phase Errors", IEEE Signal Processing Letters, vol. 17, no. 1, pp. 83-86, Jan 2010.

5. Qian He, R. S. Blum, H. Godrich, and A. M. Haimovich, "Target Velocity Estimation and Antenna Placement for MIMO Radar with Widely Separated Antennas", IEEE Journal of Selected Topics in Signal Processing, Special Issue on MIMO Radar, Vol. 4, Issue 1, pp. 79-100, Feb. 2010.

6. Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``MIMO radar waveform design via alternating projection,'' IEEE Transactions on Signal Processing, Vol. 58, Issue 3, Part 1, pp. 1440-1445, 2010.

7. Zhemin Xu, Sana Sfar, Rick S. Blum, ``Receive Antenna Selection for Closely-Spaced Antennas with Mutual Coupling", IEEE Transactions on Wireless Communications., Vol. 9, Issue 2, pp. 652-661, Feb. 2010.

8. Y. Yang, R. S. Blum and B. M. Sadler, "A Distributed and Energy-Efficient Framework for Neyman-Pearson Detection of Fluctuating Signals in Large-Scale Sensor Networks," IEEE Transactions on Selected Areas in Communications, vol. 28, no. 7, September 2010.

9. Qian He, Rick S. Blum, and Alexander M. Haimovich, "Non-coherent MIMO Radar for location and velocity estimation: More antennas means better performance", IEEE Transactions on Signal Processing, vol. 58, no. 7, pp. 3661-3680, Jul 2010.

10. Qian He, Nikolaus H. Lehmann, Rick S. Blum, Alexander M. Haimovich, and Leonard J. Cimini, "Moving Target Detection in Homogeneous Clutter with a Stationary MIMO Radar," IEEE Trans. on Aerospace and Electronic Systems, vol. 46, no. 3, pp. 1290-1301, Jul 2010.

11. Hana Godrich, Alexander M. Haimovich, and Rick S. Blum, ``Target Localization Accuracy Gain in MIMO Radar Based Systems," IEEE Trans. on Information Theory, Vol. 56, No. 6, pp. 2783-2803, June 2010.

12. Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Metrics, accepted to IEEE Trans. on Image Processing, Vol. 20, No. 2, pp. 327-344, Feb. 2011.

13. Qian He and R. S. Blum. ``Diversity Gain for MIMO Neyman-Pearson Signal Detection," IEEE Transactions on Signal Processing, Vol. 59, No. 3, pp 869-881, March 2011.

14. Rick S. Blum, "Ordering for Estimation and Optimization in Energy Efficient Sensor Networks", IEEE Transactions on Signal Processing, vol. 59, issue 6, pp. 2847-2856.

15. Min Jiang, Ruixin Niu, and Rick S. Blum,``Bayesian target location and velocity estimation for multiple-input multiple-output radar", IET Radar, Sonar & Navigation, Volume 5, Issue: 6, pp. 666 - 670, 2011.

Conf. papers
----

16 Qian He and R. S. Blum, ``Performance and complexity issues in noncoherent and coherent MIMO radar," invited paper for the 43rd IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, Nov 2009.

17 Hana Godrich , Alexander M. Haimovich and Rick S. Blum, A MIMO Radar System Approach to Target Tracking, invited

paper for 2009 Asilomar Conference on Signals, Systems and Computers.

18 Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``Waveform design for MIMO radar using an alternating projection approach,'' in Proceedings of Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, November 2009.

19 Y. Yang, R. S. Blum, Z. He, and D. R. Fuhrmann, ``Alternating projection for MIMO radar waveform design,'' invited paper for CAMSAP 2009 (Dec. 2009), pp. 169-172.

20 Chuanming Wei, Qian He, and Rick S. Blum, "Cramer-rao bound for joint location and velocity estimation in multi-target non-coherent MIMO radars", CISS 2010.

21 Xun Chen, R. S. Blum, ``Non-coherent MIMO radar in a non-Gaussian clutter-plus-noise environment,'' CISS 2010.

22 R. S. Blum, ``Ordering for Estimation", CISS 2010.

23 Y. Yang, R. S. Blum, and B. M. Sadler, ``Distributed energy-efficient scheduling for radar signal detection in sensor networks,'' 2010 IEEE International Radar Conference.

24 Qian He and R. S. Blum, "Diversity gain for MIMO radar employing nonorthogonal waveforms", invited paper for the 4th International Symposium on Communications, Control and Signal Processing, pp. 1-6, Limassol, Cyprus, Mar 2010.

25 Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Metrics, in proceeding of the 12th International Conference on Information Fusion, pp. 1076-1083, Seattle, WA, Jul. 6-9, 2009.

26 Rick S. Blum, ``Ordering for Estimation and Optimization", International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2011.

27 Qian He and Rick S. Blum, ``Smart Grid Monitoring for Intrusion and Fault Detection with New Locally Optimum Testing Procedures", ICASSP 2011.

28 Qian He and Rick S. Blum, ``MIMO Radar Diversity with Neyman-Pearson Signal Detection in Non-Gaussian Circumstance with Non-orthogonal Waveforms", ICASSP 2011.

29 Ziad Rawas, Qian He and Rick S. Blum, "Energy-Efficient Noncoherent Signal Detection for Networked Sensors Using Ordered Transmissions", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

30 Qian He and R. S. Blum, "New Hypothesis Testing-Based Methods for Fault Detection for Smart Grid Systems", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

31 Qian He and R. S. Blum. ``Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction Hypothesis Test," to appear, the 2011 IEEE International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), Chengdu, China, Sep 2011.

32 Qian He, R. S. Blum, and Zishu He. ``Noncoherent Versus Coherent MIMO Radar for Joint Target Position and Velocity Estimation," to appear, the 2011 IEEE CIE International Conference on Radar, Chengdu, China, Oct 2011.

33. H. Godrich, V. M. Chiriac, A. M. Haimovich, and R. S. Blum,
Target tracking in MIMO radar systems: Techniques and performance analysis,
2010 Radar Conference, 2010 IEEE Digital Object Identifier: 10.1109/RADAR.2010.5494453, 2010 , Page(s): 1111 - 1116.

6. Interactions/Transitions

6.1 Conference Presentations

Qian He and R. S. Blum, ``Performance and complexity issues in noncoherent and coherent MIMO radar,'' invited paper for the 43rd IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, Nov 2009.

Hana Godrich , Alexander M. Haimovich and Rick S. Blum, A MIMO Radar System Approach to Target Tracking, invited paper for 2009 Asilomar Conference on Signals, Systems and Computers.

Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``Waveform design for MIMO radar using an alternating projection approach,'' in Proceedings of Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, November 2009.

Y. Yang, R. S. Blum, Z. He, and D. R. Fuhrmann, ``Alternating projection for MIMO radar waveform design,'' invited paper for CAMSAP 2009 (Dec. 2009), pp. 169-172.

Chuanming Wei, Qian He, and Rick S. Blum, "Cramer-rao bound for joint location and velocity estimation in multi-target non-coherent MIMO radars", CISS 2010.

Xun Chen, R. S. Blum, ``Non-coherent MIMO radar in a non-Gaussian clutter-plus-noise environment,'' CISS 2010.

R. S. Blum, ``Ordering for Estimation'', CISS 2010.

Y. Yang, R. S. Blum, and B. M. Sadler, ``Distributed energy-efficient scheduling for radar signal detection in sensor networks,'' 2010 IEEE International Radar Conference.

Qian He and R. S. Blum, "Diversity gain for MIMO radar employing nonorthogonal waveforms", invited paper for the 4th International Symposium on Communications, Control and Signal Processing, pp. 1-6, Limassol, Cyprus, Mar 2010.

Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Metrics, in proceeding of the 12th International Conference on Information Fusion, pp. 1076-1083, Seattle, WA, Jul. 6-9, 2009.

Rick S. Blum, ``Ordering for Estimation and Optimization'', International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2011.

Qian He and Rick S. Blum, ``Smart Grid Monitoring for Intrusion and Fault Detection with New Locally Optimum Testing Procedures'', ICASSP 2011.

Qian He and Rick S. Blum, ``MIMO Radar Diversity with Neyman-Pearson Signal Detection in Non-Gaussian Circumstance with Non-orthogonal Waveforms'', ICASSP 2011.

Ziad Rawas, Qian He and Rick S. Blum, "Energy-Efficient Noncoherent Signal Detection for Networked Sensors Using Ordered Transmissions", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

Qian He and R. S. Blum, "New Hypothesis Testing-Based Methods for Fault Detection for Smart Grid Systems", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

Qian He and R. S. Blum. ``Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction Hypothesis Test,'' 2011 IEEE International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), Chengdu, China, Sep 2011 (to be presented).

Qian He, R. S. Blum, and Zishu He. ``Noncoherent Versus Coherent MIMO Radar for Joint Target Position and Velocity Estimation,'' the 2011 IEEE CIE International Conference on Radar, Chengdu, China, Oct 2011 (to be presented).

6.2 Transitions

There is great interest from Lockheed Martin in trying to employ the ordering technology we developed under ARO funding into future DoD Radar systems. Lockheed Martin produces what is generally thought to be the most successful DoD radar system ever produced. They are involved in projects to design future DoD radar systems and are planning to propose the MIMO radar technology we developed. They feel the ordering technology solves a number of critical issues that they face. Lockheed Martin is currently trying to put together some experimental demonstrations of our MIMO radar technology and ordering could be incorporated into these demonstrations. The contact at Lockheed is Micheal Luddy at Lockheed Martin in Moorestown, New Jersey. His email is michael.j.luddy@lmco.com.

It is also worth noting that Lockheed Martin has great interest in

MIMO radar research which was supported by this grant:

Qian He, Nikolaus H. Lehmann, Rick S. Blum, Alexander M. Haimovich, and Leonard J. Cimini, "Moving Target Detection in homogeneous Clutter with a Stationary MIMO Radar," accepted in IEEE Trans. on Aerospace and Electronic Systems expected July 2010.

which demonstrates the gains of MIMO radar systems with widely spaced antennas for moving target detection which comes from observing the target from different directions. This leads to two distinct gains that we call geometry gain and diversity gain. They have great interest in implementing this technology in future DoD radar systems.

7. Patent Disclosures
None

8. Honors
The PI was named an IEEE Signal Processing Society distinguished lecturer.

Technology Transfer

Energy Efficient Signal Detection for Army
Applications Based on Ordering, ARO Grant No.
W911NF-08-1-0449 (Submitted Sept. 2011)

Principal Investigator: Rick S. Blum
Electrical Engineering and Computer Science Dept.
Lehigh University
19 Memorial Drive West
Bethlehem, PA 18015-3084

1. Objectives

Networks of sensor nodes offer enhanced performance
along with some inherent limitations, among which the most
prominent one is probably that each sensor node is constrained
in energy supply since these nodes often carry their own energy
sources. UAVs are one example. Limited available communication
resources are also common. Under this grant, we demonstrated
that these challenges can be addressed by jointly designing the
signal processing and communications.   We developed an approach
called "ordering" where each sensor is able to judge the importance
of its data, without seeing the data at the other sensors. The
importance is judged based on the signal processing problems
the system is trying to solve, for example estimation and detection.
The sensors with the most informative data transmit their data first
and the sensors with less important data can save energy by not
transmitting. With a proper transmission stopping rule, this
approach yields the same performance as if all sensors transmit
and yet very impressive energy savings are achieved in many cases
of interest (significant SNR or number of sensors or proper system
design). We initially demonstrated the gains at the physical layer
of the communication network for networks attempting to solve signal
detection problems. Later we demonstrated appropriate higher layer
designs to capitalize on these gains while also showing the ordering
approach is appropriate for networks attempting to solve estimation,
optimization, or classification problems. We demonstrated the power
of the ordering approach on MIMO radar network examples, networks
of widely spaced antennas or radar nodes. We also made some fundamental
contributions to the theory of MIMO radar, in some cases capitalizing
on our knowledge of both communications and signal processing, and in
particular radar. The high citation rates and great interest from the
radar community (including now DoD contractors) indicate the
importance of this work.

2. Executive Summary

We have made excellent progress on studying joint design of signal
processing
and communication strategies for networks of dispersed nodes where each
node may be equipped with a sensor. One area of focus has been on
developing
appropriate signal processing and communication strategies for networks

which focus on target detection or hypothesis testing problems. There
are many important military and non-military applications of this
paradigm,
including MIMO radar which is attracting great attention in the research,
development and funding communities. MIMO radar is one focus of this
work. However, the investigations here are also much more general.
In particular, hypothesis testing, often called signal detection, is a
fundamental sensor networking application which is key for solving
many important problems including improved monitoring, control and
repair of the human body, buildings, bridges, energy production
facilities, the environment and other critical infrastructure,
while also providing important contributions to homeland security,
law enforcement, disaster prediction/avoidance and defense related
problems. For example, we had some collaboration with faculty in
the civil engineering department at Lehigh University on
monitoring the health of large structures (for example bridges, buildings
and airplanes) to detect problems before they occur. In fact there
are many applications of this type which directly fit our
paradigm. There are also some applications that indirectly fit
our paradigm. For example, we also had collaboration with
scientists in the Biological Sciences department at Lehigh
University, who are working on understanding biological systems.
In their scientific experiments they typically pose hypothesis
testing problems and attempt to test the hypothesis using sensor
measurements. Interestingly, in these applications it is important
to limit the number of measurements to avoid damaging the living
organisms under study. In this case we limit sensor measurements
for a different reason, as opposed to trying to save precious battery
power, but our general theory still applies. Of course, our main focus
has been on military applications. We have developed very promising
approaches for saving battery power and transmission rates for important
military applications employing sensors. For example, we developed a
highly efficient approach, called ordering, which saves significant
energy or transmission rate for target detection and estimation.

Out of necessity, a second area of investigation has been on developing
MIMO radar signal processing technology and also similar ideas for more
general sensor networks. In presenting and discussing some of our
research
on ordering applied to MIMO radar systems, some fundamental ideas about
MIMO radar became clear to us. As the group that is most often credited
with
initiating the current high level of interest in MIMO radar by developing
and describing the MIMO radar concept, we are still a bit ahead of others
and we were lucky to be well positioned to act quickly on some important
research opportunities that became evident. More recently we are getting
lots of interest from DoD contractors who want to employ MIMO radar ideas
into future DoD radar systems which is very exciting. These discussions
have lead to a few research discoveries which were completed under this
funding.

3. Accomplishments (all references from list in Section 5)

Our very recent work on applying ordering to estimation and optimization

problems [14,22,26] is especially exciting. A discretized version of
a continuous optimization problem is considered for the case where
data is obtained from a set of dispersed sensor nodes and the overall
metric is a sum of individual metrics computed at each sensor. An
example of such a problem is maximum likelihood estimation based on
statistically independent sensor observations [4,5,9,16,20,32]. By
ordering
transmissions from the sensor nodes, a method for achieving a saving
in the average number of sensor transmissions is described. While the
average number of sensor transmissions is reduced, the approach always
yields the same solution as the optimum approach where all sensor
transmissions occur. The approach is valid for a general optimization
or estimation problem. A maximum likelihood target location and
velocity estimation example for a multiple node non-coherent MIMO
radar system was investigated in great detail [14,22,26]. In particular,
for cases with N good quality sensors with sufficiently well designed
signals and sufficiently large signal-to-interference-plus-noise
ratio, the average percentage of transmissions saved approaches 100
percent as the number of discrete grid points in the optimization
problem Q becomes significantly large. In these same cases, the
average percentage of transmissions saved approaches (Q-1)/Q x 100
percent as the number of sensors N in the network becomes
significantly large. Similar savings are illustrated for general
optimization (or estimation) problems with sufficiently well designed
systems. Savings can be even larger in some cases for systems with
some poor quality sensors. One important result is that timing errors,
clock errors and unknown communication delays can be overcome without
significant impact in many applications [14].

We have also made some contributions to the topic of applying
ordering to signal detection problems under this grant.   The
robustness due to timing errors, clock errors and unknown
communication delays described in [14] also applies here since
[14] describes a general method to put "out of order" transmissions
back in order. We have also shown that the ordering for detection
ideas we published earlier do apply to MIMO radar systems [29].
Further, the gains for the MIMO radar application are even larger
than the gains reported earlier. First, we have provided [29] an
improved ordering approach for any noncoherent processing approach
and the MIMO radar system considered in [29] is one such approach.
Second, we show [29] that the gains are very large for practical
systems with very small false alarm probabilities. Finally, we
have discussed [8,23] a methodology for implementing ordering
approaches in radar systems by describing an efficient implementation
of some of the important subsystems required.

We have also made progress in our studies of networks of radar sensors,
showing [9,16,20,32] that we can control the performance of both the non-
coherent
and coherent approaches by the number of antennas employed. In
particular
the improvements in estimation position and velocity estimation scale
directly in proportion to the product of the number of transmitter
antennas

times the number of receiver antennas as shown in [9], and to a lesser extent
[1,4,5,11,15,16,17,20,32]. Similar gains occur for detection problems [2,10,13,21,28,29]. These estimation results [9,16] are very important in justifying the value of the noncoherent approach by showing [32] that the non-coherent approach can be made to perform sufficiently close to a coherent approach if a sufficient number of properly placed antennas are employed. Our fundamental investigations on the accuracy of the approaches for target estimation in ideal [1,5,9,11] and nonideal [4] settings have also demonstrated significant potential for MIMO radar. In fact, slow oscillator phase drifts or static phase errors may not be such a big problem [4] for MIMO radar.

MIMO radar has brought attention to diversity gains that occur in radar systems that are similar to the diversity gains that occur in communication systems. We have recently demonstrated that one needs complex targets to get these gains [2] but that orthogonal signals, Gaussian
reflections and Gaussian clutter are not needed [13]. In particular, our results in [13] show that the diversity gain of the non-coherent MIMO radar approach is not dependent on the clutter-plus-noise distribution for any well behaved (finite power) clutter model. We are particularly excited about our findings on diversity in non-Gaussian clutter-plus-noise [13]. For a radar system adopting the Neyman-Pearson (NP) criterion, we have derived the diversity gain for a general scalar hypothesis test statistic and a general vector hypothesis testing problem.

For a MIMO radar system with M transmit and N receive antennas, used to detect a target composed of Q random scatterers with possibly non-Gaussian reflection coefficients in the presence of possibly non-Gaussian clutter-plus-noise, in [13] we considered a class of test statistics, including the optimum test for Gaussian reflection coefficients and Gaussian clutter-plus-noise, and applied the previously described general (last paragraph) results to compute the diversity gain. It was found that the diversity gain for the MIMO radar system is dependent on the cumulative distribution function (cdf) of the reflected signal (and thus it depends on the distribution of the reflection coefficients) while being invariant to the cdf of the bounded variance clutter-plus-noise. If the transmitted waveforms span a dimension L, the largest possible diversity gain is no greater than $p \min(NL,Q)$, where p is the lowest order coefficient of a Taylor series expansion of the cdf of the reflected signal and L can be no greater than M. Thus orthogonal signals are not need to achieve the largest possible diversity gain of $p \min(NM,Q)$, only linear independence. In some cases of interest (independent reflections), it is shown that the maximum possible diversity gain can be achieved.

We were also able to demonstrate [10] a new gain, called geometry gain, in MIMO radar moving target detection applications that looks a bit like a diversity gain but which is distinctly different. It comes from viewing the motion of the target from different directions and developing the estimated (fused) motion to be consistent with all these views. We have received some significant interest from industry in these results

due to the practical importance and difficult nature of this problem.
Similarly, industry and academia are both very interested in waveform
design for MIMO radar. We have studied this problem for classification
and high resolution estimation applications in [6,18,19]. Here we were
able to extend some of our previous theoretical results that showed an
equivalence between optimizing for mean-square error and mutual
information.
The previous results demonstrated the equivalence without producing the
actual waveforms. In [6,18,19], we provided an algorithm to produce
actual waveforms and we showed these practical waveforms produced results
that were indistinguishable from our previous theoretical predictions in
a large number of example cases considered. Thus, these practical
waveforms
jointly optimized mean-square error and mutual information for the
example
cases considered to the highest accuracy we could achieve in our
computations.
We were recently the first group to demonstrate large potential gains in
tracking
performance from employing a MIMO radar and in [17,33] we study the
effect
of the antenna positions, target location, path loss, target
reflectivity,
and the number of antennas (radar nodes) employed.

Some other contributions to image fusion, communications and smart
grid are reported in [3,7,12,,25,27,30,31]. Here we have tried to use
some of
the ideas and techniques studied under this funding for some different
applications
from those previously considered, mainly radar and sensor networking.

4. Personnel Supported

Rick S. Blum, (PI) Professor of ECE
Xun Chen, Research Assistant
Jim Davis, Research Assistant
Ziad Rawas, Research Assistant
Zhemin Xu, Research Assistant
Qian He, Research Assistant
Yang Yang, Research Assistant
Anand Srinivas Guruswamy, Research Assistant
Joe Baker, Research Assistant
Chuanming Wei, Research Assistant
Liang Zhao, Research Assistant
Qian He, postdoc
Yang Yang, Postdoc

5. Technical Publications

Journal Papers
----

1. Hana Godrich, Alexander Haimovich, Rick S. Blum, ``Target Localisation Techniques
and Tools for multiple-input multiple-output radar,'' Radar, Sonar & Navigation, IET,
Vol. 3, Issue 4, pp. 314-327, Aug. 2009.

2. Rick S. Blum, "Limiting Case of a Lack of Rich Scattering Environment for MIMO Radar
Diversity'', IEEE Signal Processing Letters, Volume 16, Issue 10, Oct. 2009, pp. 901-904.

3. Chuanming Wei and Rick S. Blum, ``Theoretical analysis of correlation-based quality measures
for weighted averaging image fusion,''Information Fusion (10 November 2009).

4. Qian He, Rick S. Blum, "Cramer-Rao Bound for MIMO Radar Target Localization with Phase Errors'',
IEEE Signal Processing Letters, vol. 17, no. 1, pp. 83-86, Jan 2010.

5. Qian He, R. S. Blum, H. Godrich, and A. M. Haimovich, "Target Velocity Estimation and Antenna
Placement for MIMO Radar with Widely Separated Antennas'', IEEE Journal of Selected Topics in
Signal Processing, Special Issue on MIMO Radar, Vol. 4, Issue 1, pp. 79-100, Feb. 2010.

6. Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``MIMO radar waveform design via alternating
projection,'' IEEE Transactions on Signal Processing, Vol. 58, Issue 3, Part 1, pp. 1440-1445, 2010.

7. Zhemin Xu, Sana Sfar, Rick S. Blum, ``Receive Antenna Selection for Closely-Spaced Antennas with Mutual
Coupling'', IEEE Transactions on Wireless Communications., Vol. 9, Issue 2, pp. 652-661, Feb. 2010.

8. Y. Yang, R. S. Blum and B. M. Sadler, "A Distributed and Energy-Efficient Framework for Neyman-Pearson
Detection of Fluctuating Signals in Large-Scale Sensor Networks," IEEE Transactions on Selected Areas
in Communications, vol. 28, no. 7, September 2010.

9. Qian He, Rick S. Blum, and Alexander M. Haimovich, "Non-coherent MIMO Radar for location and velocity
estimation: More antennas means better performance'', IEEE Transactions on Signal Processing, vol. 58,
no. 7, pp. 3661-3680, Jul 2010.

10. Qian He, Nikolaus H. Lehmann, Rick S. Blum, and Alexander M. Haimovich, "MIMO Radar Moving Target
Detection in Homogeneous Clutter,'' IEEE Trans. on Aerospace and Electronic Systems, vol. 46, no. 3,
pp. 1290-1301, Jul 2010.

11. Hana Godrich, Alexander M. Haimovich, and Rick S. Blum, ``Target Localization Accuracy Gain in MIMO
Radar Based Systems,'' IEEE Trans. on Information Theory, Vol. 56, No. 6,
pp. 2783-2803, June 2010.

12. Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, "Diffuse Prior Monotonic Likelihood
Ratio Test for Evaluation of Fused Image Quality Measures", IEEE Trans. on Image Processing, Vol. 20, No. 2,
pp. 327-344, Feb. 2011.

13. Qian He and R. S. Blum. ``Diversity Gain for MIMO Neyman-Pearson Signal Detection,'' IEEE Transactions
on Signal Processing, Vol. 59, No. 3, pp 869-881, March 2011.

14. Rick S. Blum, "Ordering for Estimation and Optimization in Energy Efficient Sensor Networks", IEEE
Transactions on Signal Processing, vol. 59, issue 6, pp. 2847-2856.

15. Min Jiang, Ruixin Niu, and Rick S. Blum,``Bayesian target location and velocity estimation for
multiple-input multiple-output radar'', IET Radar, Sonar & Navigation, Volume 5, Issue: 6,
pp. 666 - 670, 2011.

Conf. papers
----

16 Qian He and R. S. Blum, ``Performance and complexity issues in noncoherent and coherent MIMO radar,''
invited paper for the 43rd IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove,
CA, Nov 2009.

17 Hana Godrich , Alexander M. Haimovich and Rick S. Blum, A MIMO Radar System Approach to Target Tracking,
invited paper for 2009 Asilomar Conference on Signals, Systems and Computers.

18 Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``Waveform design for MIMO radar using an alternating
projection approach,'' in Proceedings of Asilomar Conference on Signals, Systems, and Computers, Pacific
Grove, CA, November 2009.

19 Y. Yang, R. S. Blum, Z. He, and D. R. Fuhrmann, ``Alternating projection for MIMO radar waveform design,''
invited paper for CAMSAP 2009 (Dec. 2009), pp. 169-172.

20 Chuanming Wei, Qian He, and Rick S. Blum, "Cramer-rao bound for joint location and velocity estimation
in multi-target non-coherent MIMO radars", CISS 2010.

21 Xun Chen, R. S. Blum, ``Non-coherent MIMO radar in a non-Gaussian clutter-plus-noise environment,''
CISS 2010.

22 R. S. Blum, ``Ordering for Estimation", CISS 2010.

23 Y. Yang, R. S. Blum, and B. M. Sadler, ``Distributed energy-efficient scheduling for radar signal
detection in sensor networks,'' 2010 IEEE International Radar Conference.

24 Qian He and R. S. Blum, "Diversity gain for MIMO radar employing nonorthogonal waveforms", invited
paper for the 4th International Symposium on Communications, Control and Signal Processing, pp. 1-6,
Limassol, Cyprus, Mar 2010.

25 Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood
Ratio Test for Evaluation of Fused Image Quality Metrics, in proceeding of the 12th International
Conference on Information Fusion, pp. 1076-1083, Seattle, WA, Jul. 6-9, 2009.

26 Rick S. Blum, ``Ordering for Estimation and Optimization", International Conference on Acoustics,
Speech and Signal Processing (ICASSP) 2011.

27 Qian He and Rick S. Blum, ``Smart Grid Monitoring for Intrusion and Fault Detection with New Locally
Optimum Testing Procedures", ICASSP 2011.

28 Qian He and Rick S. Blum, ``MIMO Radar Diversity with Neyman-Pearson Signal Detection in Non-Gaussian
Circumstance with Non-orthogonal Waveforms'', ICASSP 2011.

29 Ziad Rawas, Qian He and Rick S. Blum, "Energy-Efficient Noncoherent Signal Detection for Networked
Sensors Using Ordered Transmissions", Conference on Information Sciences and Systems, Johns Hopkins,
March 2011.

30 Qian He and R. S. Blum, "New Hypothesis Testing-Based Methods for Fault Detection for Smart Grid Systems",
Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

31 Qian He and R. S. Blum. ``Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction
Hypothesis Test,'' to appear, the 2011 IEEE International Conference on Smart Grid and Clean Energy
Technologies (ICSGCE), Chengdu, China, Sep 2011.

32 Qian He, R. S. Blum, and Zishu He. ``Noncoherent Versus Coherent MIMO Radar for Joint Target Position and
Velocity Estimation,'' to appear, the 2011 IEEE CIE International Conference on Radar, Chengdu, China, Oct
2011.

33. H. Godrich, V. M. Chiriac, A. M. Haimovich, and R. S. Blum, Target tracking in MIMO radar systems: Techniques and performance analysis,
2010 Radar Conference, 2010 IEEE Digital Object Identifier: 10.1109/RADAR.2010.5494453
Publication Year: 2010 , Page(s): 1111 - 1116.

6.   Interactions/Transitions

6.1 Conference Presentations

Qian He and R. S. Blum, ``Performance and complexity issues in noncoherent and coherent MIMO radar,''
invited paper for the 43rd IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove,
CA, Nov 2009.

Hana Godrich , Alexander M. Haimovich and Rick S. Blum, A MIMO Radar System Approach to Target Tracking,
invited paper for 2009 Asilomar Conference on Signals, Systems and Computers.

Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``Waveform design for MIMO radar using an alternating
projection approach,'' in Proceedings of Asilomar Conference on Signals, Systems, and Computers, Pacific
Grove, CA, November 2009.

Y. Yang, R. S. Blum, Z. He, and D. R. Fuhrmann, ``Alternating projection for MIMO radar waveform design,''
invited paper for CAMSAP 2009 (Dec. 2009), pp. 169-172.

Chuanming Wei, Qian He, and Rick S. Blum, "Cramer-rao bound for joint location and velocity estimation
in multi-target non-coherent MIMO radars", CISS 2010.

Xun Chen, R. S. Blum, ``Non-coherent MIMO radar in a non-Gaussian clutter-plus-noise environment,''
CISS 2010.

R. S. Blum, ``Ordering for Estimation", CISS 2010.

Y. Yang, R. S. Blum, and B. M. Sadler, ``Distributed energy-efficient scheduling for radar signal
detection in sensor networks,'' 2010 IEEE International Radar Conference.

Qian He and R. S. Blum, "Diversity gain for MIMO radar employing nonorthogonal waveforms", invited

paper for the 4th International Symposium on Communications, Control and Signal Processing, pp. 1-6,
Limassol, Cyprus, Mar 2010.

Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood
Ratio Test for Evaluation of Fused Image Quality Metrics, in proceeding of the 12th International
Conference on Information Fusion, pp. 1076-1083, Seattle, WA, Jul. 6-9, 2009.

Rick S. Blum, ``Ordering for Estimation and Optimization", International Conference on Acoustics,
Speech and Signal Processing (ICASSP) 2011.

Qian He and Rick S. Blum, ``Smart Grid Monitoring for Intrusion and Fault Detection with New Locally
Optimum Testing Procedures", ICASSP 2011.

Qian He and Rick S. Blum, ``MIMO Radar Diversity with Neyman-Pearson Signal Detection in Non-Gaussian
Circumstance with Non-orthogonal Waveforms'', ICASSP 2011.

Ziad Rawas, Qian He and Rick S. Blum, "Energy-Efficient Noncoherent Signal Detection for Networked
Sensors Using Ordered Transmissions", Conference on Information Sciences and Systems, Johns Hopkins,
March 2011.

Qian He and R. S. Blum, "New Hypothesis Testing-Based Methods for Fault Detection for Smart Grid Systems",
Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

Qian He and R. S. Blum. ``Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction
Hypothesis Test,'' 2011 IEEE International Conference on Smart Grid and Clean Energy
Technologies (ICSGCE), Chengdu, China, Sep 2011 (to be presented).

Qian He, R. S. Blum, and Zishu He. ``Noncoherent Versus Coherent MIMO Radar for Joint Target Position and
Velocity Estimation,'' the 2011 IEEE CIE International Conference on Radar, Chengdu, China, Oct
2011 (to be presented).

6.2 Transitions

There is great interest from Lockheed Martin in trying to employ the ordering technology we developed under ARO funding into future DoD Radar systems. Lockheed Martin produces what is generally thought to be the most
successful DoD radar system ever produced. They are involved in projects to

design future DoD radar systems and are planning to propose the MIMO radar
technology we developed. They feel the ordering technology solves a number
of critical issues that they face. Lockheed Martin is currently trying to put
together some experimental demonstrations of our MIMO radar technology and
ordering could be incorporated into these demonstrations. The contact
at Lockheed is Micheal Luddy at Lockheed Martin in Moorestown,
New Jersey. His email is michael.j.luddy@lmco.com.

It is also worth noting that Lockheed Martin has great interest in
MIMO radar research which was supported by this grant:

Qian He, Nikolaus H. Lehmann, Rick S. Blum, Alexander M. Haimovich,
and Leonard J. Cimini, "Moving Target Detection in homogeneous Clutter
with a Stationary MIMO Radar,'' accepted in IEEE Trans. on Aerospace
and Electronic Systems expected July 2010.

which demonstrates the gains of MIMO radar systems with widely spaced
antennas for moving target detection which comes from observing the
target from different directions. This leads to two distinct gains
that we call geometry gain and diversity gain. They have great
interest in implementing this technology in future DoD radar systems.

7. Patent Disclosures
None

8. Honors
The PI was named an IEEE Signal Processing Society distinguished
lecturer.